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Who Controls Energy in the Smart Home? A Multidisciplinary Taxonomy
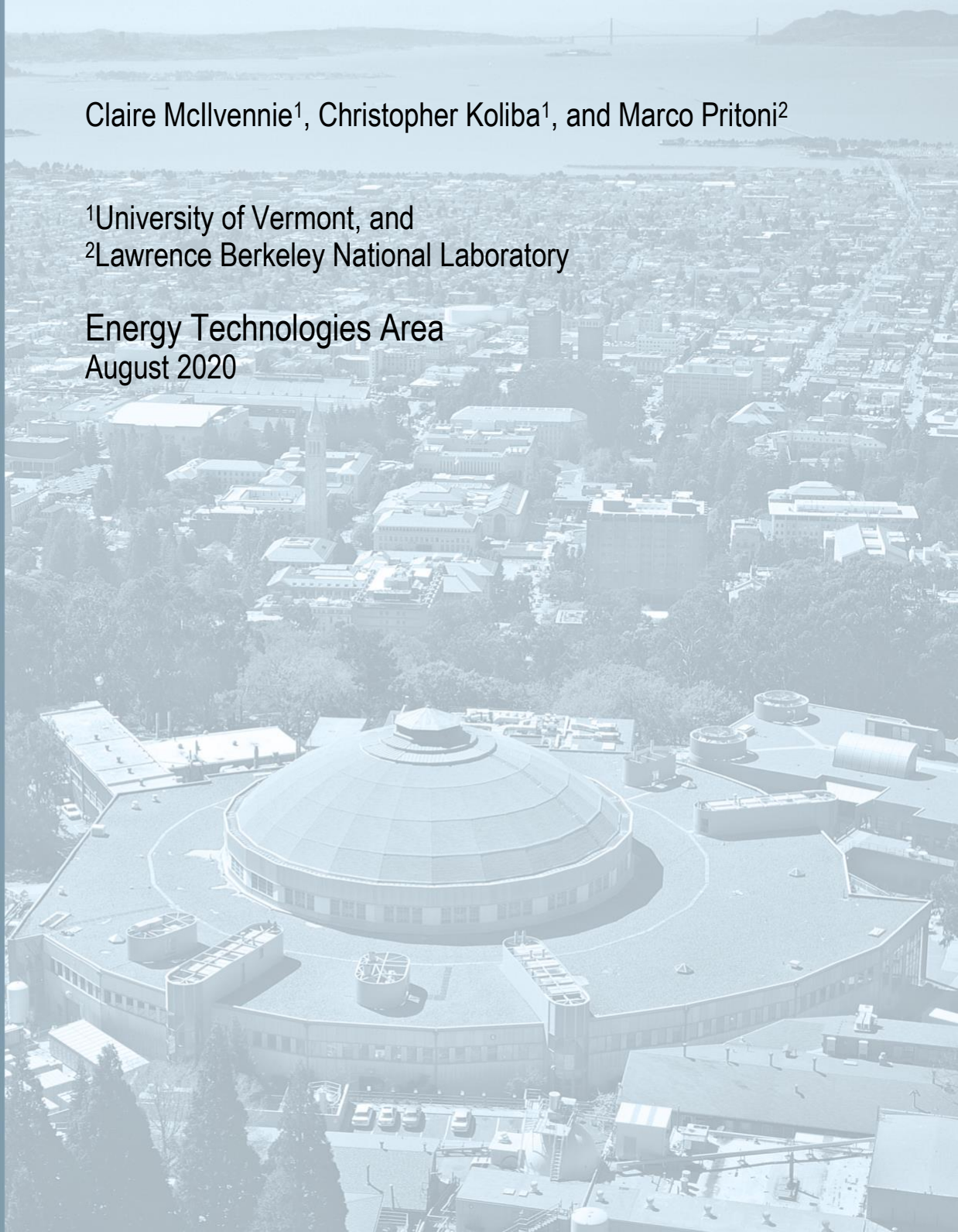
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ABSTRACT

Advances in technology have begun to open new opportunities for behavior-based and technical approaches to managing residential energy use and meet sustainability-related objectives. Visions of the future predict homes with smart technologies delivering enhanced comfort and cost savings to residents; utility-partners who can remotely optimize energy resources to meet grid needs; and occupants who play more active roles in the energy system supported by advanced information communication technologies. Each of these scenarios implies augmented control over home energy use, yet uncertainties remain regarding which ones will deliver the greatest grid benefits and services to customers in a given situation. These scenarios also raise broader questions regarding customer agency and the relationship between customers and third parties moving forward. While both the provision of information to spur behavior change and automated technologies theoretically enhance control over energy use in the built environment, these strategies are not often studied from an integrated perspective. Seeking to address this gap and develop a deeper understanding of the evolving paradigm of control over home energy use, this paper presents a taxonomy to evaluate perspectives from public policy (ex. demand-side management), technological innovation (automated controls), and user-agency (ex. the role of behavior change) on approaches to managing home energy use. We draw on theoretical and empirical evidence from across disciplines to detail the dimensions and implications of deploying programs that incorporate various levels of control and anticipate such a taxonomy will help holistically map out and evaluate tradeoffs between different approaches to demand-side management moving forward.

Introduction

As the energy system undergoes a transition towards intermittent and distributed energy resources and a wave of technical innovation, such as smart home energy monitors and appliances with built-in automation, enters the home, the roles of actors in the energy system are being redefined (Darby 2018; Hansen et al 2020). In the residential sector, many stakeholders expect households to evolve from relatively static actors in the system towards more active participants contributing to the balancing of supply and demand-side resources enabled by an influx of technologies that unlock new forms of control over energy (Goulden et al. 2014; Smale, Spaargarden, and van Vliet, 2019). As noted by Darby and Pisica (2013, 2322), "As smart grids are developed, we are seeing the end of the simple divide between 'the supply side' and 'consumers', and the beginning of more complex arrangements which require new rules and systems to be negotiated and designed" .

As demand-side solutions integrate with supply-side considerations, questions of agency have been raised regarding which actors (ex. residents or utilities) should be in control of in-

home systems to manage energy use in a way that delivers on sustainability- and grid-related goals and objectives (Creutzig et al. 2018). While residents of a home have traditionally been the actors with the most direct agency over energy use, the presence of smart technologies in the home has begun to shift the balance of power. Wilhite and Diamond (2017, 52) note that while consensus around a definition of the smart home or smart technologies does not exist, "the essence of the 'smart' transformation is a transfer of agency from householders to an array of technologies and structural elements that contribute to the production of energy services such as lighting, cleaning, cooking, heating, and cooling". In the context of demand-side management (DSM), or efforts to shift patterns of customer energy use, this transfer also implicates flows of agency between residents and third parties, such as utilities, via smart technologies and the Internet of Things.

As technologies become more prevalent in the home, many stakeholders assume that more technical automation will lead to reductions in total energy use and peak demand (Hargreaves and Wilson 2017). Such assumptions rely on technologies offering optimized control over energy-dependent end uses within the home, degrees of control that might not otherwise occur if decisions are left to boundedly rational residents. Of course, this assumption rests on a second set of assumptions, that smart technologies will be designed and used (or not used) by residents in such a way to deliver expected benefits and that residents are willing to allow their devices to operate in a way that prioritizes energy use, including giving up control to parties external to their home.

Yet smart technologies may also mediate the ways in which people use resources through shaping human behavior itself (Midden, Kaiser, & McCalley, 2007). This can be done through mechanisms such as enhanced feedback features and engaging and activiting user motivation to use resources in a specific way. Work initiated by Fogg (1998; 2002) on persuasive technologies explores computing technologies as new social actors, where information provided by the technologies seeks to shape or reinforce behaviors on a given issue, such as sustainable consumption of energy. The design of such technologies aims to change behavior and provide social cues that provoke specific social responses from their human users (Fogg 2002). While enhanced automation often seeks to exclude users from resource use decisions and give control to the technologies or third parties via these technologies, the provision of information, such as social norms and tips or nudges regarding how to reduce energy use, seeks to enhance control of the human themselves.

Questions remain regarding each of these two scenarios: How much control do residents actually want or need over devices in their home? How willing will they be to delegate control to outside parties or technologies themselves? What configurations of control will be most successful at producing desired outcomes? Although research has begun to explore these dynamics, evidence remains limited and there have been calls for greater clarity regarding what the industry means by the "smart home", the roles of the actors within it, and its contribution to energy system transitions towards a resilient and sustainable energy future (Randall 2003; Darby 2018).

As such, this work proposes a multidisciplinary taxonomy of control in the smart home to enhance understanding of how various smart technology-enabled strategies implicate control over energy use. The use of the taxonomy will support systematic assessments of the ways assumptions about different actors and their agency might influence the ability to realize potential energy benefits, such as reductions in overall energy use, load management, or cost savings. To develop the taxonomy, we draw on empirical and theoretical evidence across

disciplines, and believe it will serve as a valuable tool to investigate the various mechanisms through which control over energy can be employed, the implications of employing certain strategies over others, and understanding where assumptions built into expected impacts might be incorrect.

The paper proceeds as follows: we begin by defining the smart home with regards to two dimensions: the actors operating within the system and the types of control available to them. Given these dimensions, we propose a taxonomy of smart home control, identifying four smart home solution spaces and defining each space with regards to the agency given to different actors and the types of control they employ. We conclude with a discussion of future work in this field.

Defining the Smart Home: Actors

The smart home is a complex system made up of a diverse set of actors. Depending on their agency within the system, different actors hold the ability to create change or produce a particular or desired impact. Within this taxonomy, we focus on those entities that have the ability to control home energy use and consider three actors in particular: the residents of the home, third party stakeholders, and smart technologies.

Residents

Residents represent individuals or groups of individuals within a residential building that interact with each other, material infrastructures (ex. technologies), and external parties (ex. utilities) in ways that influence energy consumption. Across the literature they are also often referred to as "users" or "occupants". Smart homes are expected to bring a variety of benefits to residents, with many of these benefits centered around finer control over end uses (such as appliances) and providing enhanced services or lifestyle benefits around comfort, simplicity, entertainment, health, security, and convenience (Strengers and Nicholls 2017; Wilhite and Diamond, 2017). While managing and saving energy and the related costs are also a recognized potential benefit to residents, they are not always the primary ones (Sanguinetti et al. 2018).

Third Parties

Third party actors represent those entities that operate externally to the home and seek to manage home energy use in a way that contributes services to the grid, supporting the delivery of safe and reliable power to customers. Traditionally, third party actors have been utility service providers, but the development of the smart home has introduced new actors to this space. These actors include aggregators who contract with utilities or energy markets to provide grid resources, such as demand flexibility (Hansen and Hauge 2017). Smart technologies are expected to help third parties meet objectives around enhanced energy efficiency and resident engagement (Elliot Molina and Trombley 2012; Lange et al. 2018) and the integration of renewable energy resources onto the grid through unlocking greater demand responsive and flexible resources (ENERGY STAR 2020).

Smart Technologies

Smart technologies include material infrastructures or software platforms within the home that provide services to residents and third parties. Definitions of smart technologies differ, ranging from technologies that offer programmable options with interactive displays to those that are focused more narrowly on the internet of things and automated controls (Wilhite and Diamond 2017) supported by artificial intelligence and the ability for third parties to remotely control end uses. For the purpose of this work, we consider smart technologies as those that offer information and/or automated controls to their users (Ford et al. 2016). Within the realm of home energy use research, these technologies are typically referred to as home energy management technologies (HEMS; ex. Karlin et al. 2015; Ford et al. 2016), smart home energy management systems (SHEMS; ex. ENERGY STAR 2020), or smart home technologies (SHT; ex. Wilson and Hargreaves 2017; Herrero Nicholls and Strengers 2018). Smart technologies generally fall into one of three categories of products: user interfaces like in-home displays (IHDs) or smartphone applications, smart hardware like smart thermostats, and software platforms, such as those that provide data analytics (Ford et al. 2016). Two functionalities of smart technologies drive their expected capacity to deliver energy benefits: their ability to provide greater flows of information and automated controls between actors in the system (Ford et al. 2017).

Automated controls. Smart technologies provide various degrees of automated control between the actors within the system. These products offer two particular types of control: remote control and algorithmic control. With remote control, users of the technologies (ex. residents or third parties) remotely control end uses in the home through smart interfaces. With algorithmic control, smart technologies are used to schedule or automate operation of the device according to preferences provided by other actors in the system, such as residents or third parties. In addition, algorithmic control can optimize operation of home appliances based on historical data through algorithms, such as machine learning (Karlin et al. 2015).

Provision of information. Information relates to the provision of data regarding energy consumption to an actor within or external to the home. While increased control over energy use is often thought of from a technical control perspective, the provision and manipulation of information through mechanisms such as feedback also implicates control through influence on human behavior, as suggested by the field of cybernetics (Karlin, Ford, & Squiers, 2014). In the realm of home energy use, such informtion could include raw data (ex. feedback regarding kWhs consumed or dynamic pricing information) and analyzed data (ex. feedback regarding energy consumption trends over a given period or tips regarding how to manage usage). Information provided by smart technologies is envisioned as an opportunity to engage residents as an integrated part of the energy system and encourage them to change their behavior in ways that meet energy system needs (Goulden et al. 2014), while also providing third parties more fine-grained information on energy use patterns.

Agency in the Smart Home

Figure 1 illustrates the smart home system, characterized by these three types of actors and the flows of information and technical controls between them. Actors are represented by boxes with icons, and information and technical control are illustrated by the arrows between them. Red arrows indicate flows of control (either automation or information-based) and blue

arrows show flows of information between actors. While **Figure 1** represents new flows of information enabled by smart technologies, it also illustrates where more traditional flows of information might exist as well (ex. energy consumption data provided by a utility to a resident through a bill or home energy report). Any of the three actors could have primary agency within the system depending on the types of smart home solutions being employed and that agency could be enhanced or inhibited based on the availability of information and/or control opportunities. The impacts of smart home solutions are ultimately related to the operation of energy-dependent end-uses, such as appliances, HVAC systems, or electronics, within the home, which can change based on direct actions by residents or smart technologies, or indirect actions by third parties.
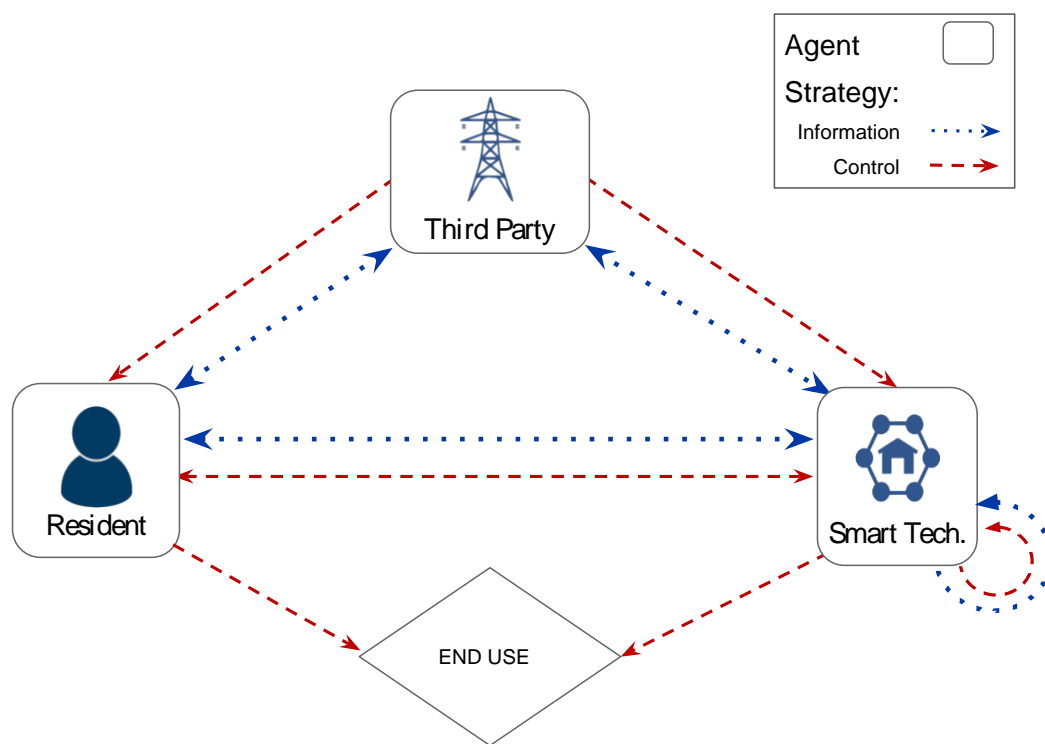

Figure 1. Representation of the actors within smart home systems based on flows of information and control. Adapted from McIlvennie, Sanguinetti, & Pritoni (2020).

It is worth noting that smart technologies are fundamentally different from the other two actors within the system with regards to their agency. While residents and third parties each seek to optimize energy use for different reasons such as thermal comfort or meeting energy efficiency targets, smart technologies are different in that they do not inherently optimize their behavior to achieve their own goals, but operate with regards to the preferences or boundaries set by the other actors within the system. So, while some smart technologies have agency within this system, it is bound by the objectives of other actors.

Defining the Smart Home: Degrees of Control

For the purpose of this taxonomy we focus on the concept of control as it relates the ability to manage devices, human behavior, and/or events (Revell and Stanton 2018) and the related impacts on energy use. We build on existing work in the field (ex. Elliot Molina and Trombly 2012; Karjalainen 2013) that asserts opportunities for smart or intelligent controls exist on a spectrum, ranging from human behavior driven control on one end to fully automated, technical systems on the other. In particular, we identify three degrees of control: manual control (resident-driven), technical control (full automation), and mixed control.

Manual (Resident-driven) Control

On one end of the spectrum, control in the smart home is driven exclusively by decisions made by the residents themselves. Here, residents take all actions within the system with no assistance from automated controls. Instead, the role of smart technologies is to provide greater access to information and tools to reduce energy use (Elliot Molina and Trombley 2012). Efforts to influence energy use on this end of the spectrum focus on the ability to change behavior in a way that reduces or shifts energy use and include efforts to provide energy feedback, information on dynamic pricing, or nudges about when to use different appliances. Significant research exists within the social sciences and field of human-computer interaction seeking to understand how to present this information to achieve desired goals (Sanguinetti Dombrovski and Sikand 2018) and a long history of research on energy use has shown the extent to which social influence and feedback can generate and manage change (Cialdini and Trost 1998, Ehrhardt-Martinez, Donnelly, and Laitner, 2010; Faruqui and Sergici 2013; Sussman and Chikumbo 2016). Although a core proposition of smart home technologies asserts they will enhance feelings of control within their users, (Strengers et al. 2016; Hargreaves and Wilson, 2017) a minority of the focus seem to envision residents actively engaging with smart technologies and the functionalities they afford (Nyborg 2015; Wilson and Hargreaves 2017).

Technical (Fully Automated) Control

At the other end of the spectrum, control is provided by fully automated systems with minimal human input. In this scenario, the resident provides the basic programming for the device (Elliot Molina and Trombley 2012) and consent to automation, and then allows automation to make all decisions thereafter (Karjalainen 2013). Here, smart technologies effectively aim to remove the real-time, in-situ human behavioral element in favor of technical optimization supported by building sensors and controls. Many visions of the smart home focus on the combination of technically automated functionalities of smart technologies with relatively passive residents to drive energy benefits. Example programs include those around smart thermostats that learn resident behaviors and optimize temperatures accordingly or automated lighting systems that sense resident occupancy or absence.

Mixed Control

In between these two extremes, smart home systems allow for shared control by both the residents and smart technologies. With mixed control, smart technologies might inform resident decision-making by providing a suite of possible actions based on historical data and allowing

the resident to pick one or executing a particular action and then providing the resident with feedback on the decisions that were made and the associated impacts (Karjalainen 2013). Past research on building automation has cautioned against overreliance on full automation to achieve desired energy and sustainability related outcomes (Cole and Brown 2009; Karjalainen 2013; Day and Heschong 2016) and mixed control opportunities could serve to address these concerns. Research on smart controls in residential settings has observed the ability for enhanced technical control mechanisms to make users feel controlled by the technologies, resulting in a feeling of lack of control in their own homes (Randall 2003; Davidoff et al 2006; Fell et al 2015). Mixed control opportunities could provide a way to counter these effects, as past work has suggested that involving users of technologies in the process of managing devices can enhance feelings of control, even if some of it is actually being delegated to technology (Langer 1975; Hargreaves and Wilson 2017; Pisharoty et al 2015).

Smart Home Control: A Taxonomy

These two dimensions of the smart home (i.e. the key actors and degrees of control) provide the foundation of our taxonomy. We visualize this taxonomy in **Figure 2** as a grid space. The x-axis represents the degrees of control, ranging from resident-driven control on one end to full automation on the other. In addition, we add the y-axis representing a spectrum of **agency** with regards to those actors capable of taking actions within the home. This continuum delineates the extent to which control over energy is exercised primarily from a perspective of individual agency by residents versus collective, grid-focused agency exercised by third parties. The middle of the y-axis represents the agency space of the smart technologies, mediating between these two extremes.

With this foundation, **Figure 2** seeks to provide a holistic representation of potential smart home configurations by affording the opportunity to systematically map out the ways in which solutions might impact energy use. Within this taxonomy, we identify four smart home solutions spaces, defined by different configurations of control and agency, each illustrated by a version of the smart home conceptual map presented in **Figure 1.** As we define the four profiles, we illustrate them using an example use-case based on the implementation of smart thermostats and their ability to drive energy benefits.
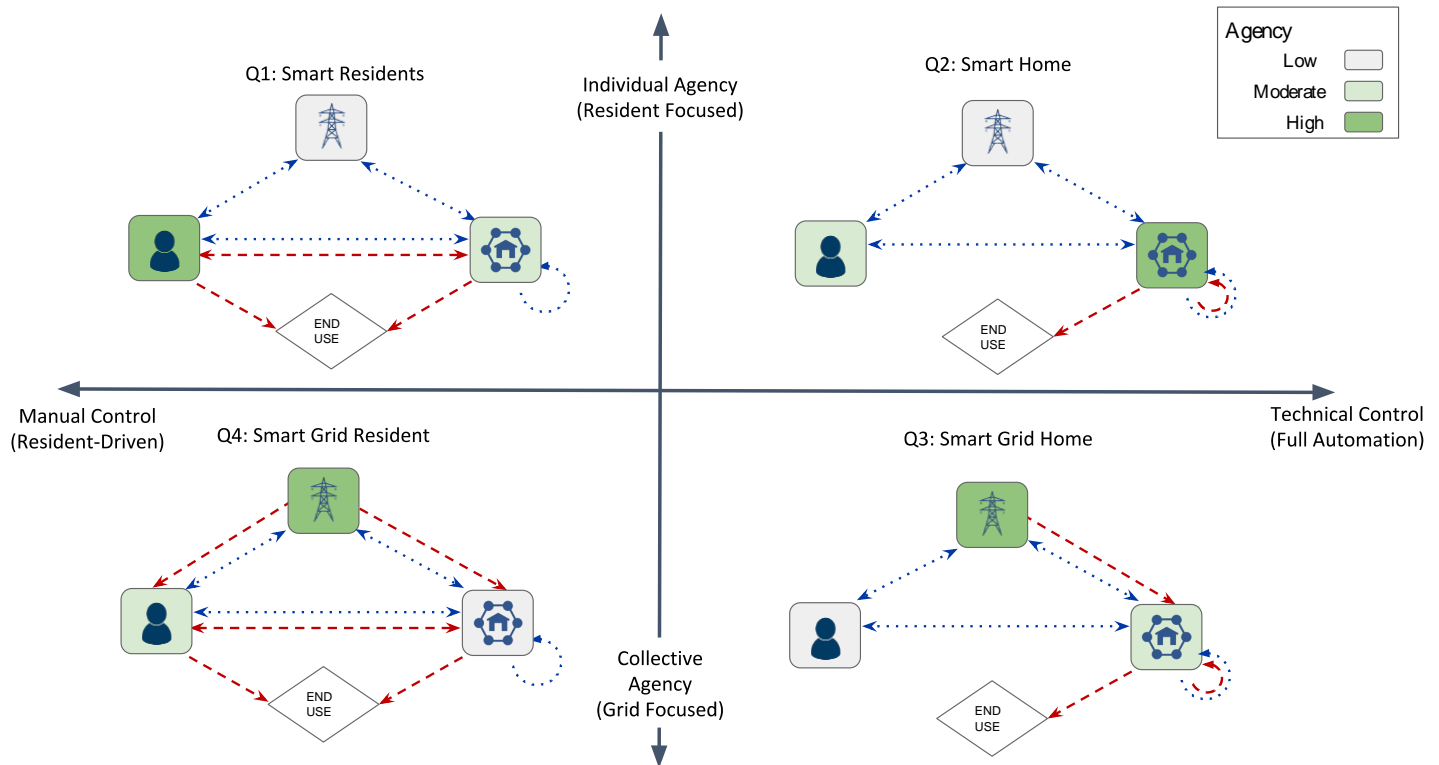
Figure 2. Visualization of the Taxonomy for Control in the Smart Home.

Quadrant One: Smart Residents

The top left quadrant represents the configuration of "smart residents". Agency focuses on the individual residents who exert manual control over end uses. The smart technologies serve to provide residents with greater information on home energy use and remote control over energy using devices. Within this quadrant, as DSM efforts move from full manual control towards the origin, individuals increasingly interact with the automated functionalities of the smart technologies, engaging more fully with the information they provide and some level of remote control (ex. choosing between actions suggested by the smart technologies). Control over energy use occurs through behavioral changes and decisions made by the residents regarding how they interact with energy-related end uses (represented by the red arrow from the resident to the end use) or through remote control of end uses initiated by the resident and carried out by the smart technologies (represented by the sequence of red arrows stemming from the resident, to the smart technology, and then to the end use). Throughout these interactions, the smart technologies may provide the resident with some form of feedback on the implications of their choices, and the third parties may provide the resident information related to energy system needs, for example by presenting information on dynamic rates, but ultimately the decisions and actions lie with the resident and require their persistent engagement to drive energy benfits such as reductions in consumption or load management.

Example thermostat use case: Within this type of home, smart thermostats would operate much the same as a programmable thermostat, which allows users to provide bounds for set points or specific hours of operations, coupled with an interactive interface or smart home energy monitor

(such as that discussed in Lange et al. 2018). Through the monitor, residents would be exposed to greater information on their heating and cooling systems and potentially even receive feedforward information (Pisharoty et al. 2015) regarding different set point options and related outcomes regarding comfort, cost, and/or energy savings. Here, projected energy benefits rely on engaged residents capable of understanding the implications of energy use based on information provided by smart devices who are then motivated to prioritize and take action that will impact energy use in specific ways.

Quadrant Two: The Smart Home

The second quadrant represents smart home configurations that emphasize individual agency supported by predominantly technical, automation-based control opportunities. The ability to manage energy use still lies in the agency of the residents, focusing on their desires for and needs around comfort, cost savings, environmental conservation, or potentially energy management. Thus, if the resident prefers comfort to energy conservation, the potential for increased energy use exists. While agency is focused on the individual level, these residents delegate control to automated functionalities of the smart technology, meaning smart technologies hold primary agency in this system. While both residents and third parties may initially provide information to the smart technology to set general boundaries of action, the latter actor decides how energy is used within the home, optimizing based on those operational bounds provided to it, and giving priority to the needs of the resident over that of the grid. At the extreme, this type of smart home is defined by fully automated systems without interaction with the resident, as represented in the diagram by the fact the only control pathways (red arrows) appear between the smart technologies and end uses.

Example thermostat use case: Within this type of home, the resident would install the smart thermostat and provide information on preferred temperature setpoints, but machine learning built into the devices (algorithmic control) would take this information and, combined with historical data, in theory learn the behavior of the residents. The thermostat would then optimize energy use accordingly. Energy management potential in this scenario assumes that once programmed, the resident will leave the device to operate on its own and that management of energy use by the device will prove more efficient than by the resident.

Quadrant Three: Smart Grid Home

The third solution space represents smart grid homes, which operate under a scenario of high grid-focused agency that materializes through partial or full automation. Third parties hold the highest levels of agency, followed by smart technologies, and residents. Within these homes, the focus is on providing services to the grid based on actions taken by smart technologies on behalf of third parties. Control stems from third parties either remotely controlling end uses through smart technologies (as a form of direct load control) or smart technologies optimizing household energy use according to parameters provided by the third party actors. While residents might still provide preferred operating bounds and could in theory override actions of the smart technologies, preference here is given to the needs of the grid as the default. Similar to the smart home profile, the assumption underlying expected energy benefits is that the resident is effectively absent from the system, allowing end uses to be optimized according to the needs of the grid, much like third party owned resources such as utility scale solar might be.

Example thermostat use case: In the smart thermostat use case, third parties and the "smart" capabilities of the thermostat automatically take action without involvement of the resident to control energy use based on the needs of the grid. Example programs here include the Rush Hour Rewards program by Nest and a variety of US utilities that automatically adjust home thermostats to accommodate needs to reduce demand during specified peak events (Nest Labs Inc 2014). While customers in this particular type of home have the ability to override the smart thermostat and adjust setpoints manually, the assumption underlying grid benefits is that, on average, they won't. A more extreme version of programs in this space might take programs like Rush Hour Rewards and extend them more broadly, asking residents to allow third parties to control their thermostat in real time according to the needs of the grid.

Quadrant Four: Smart Grid Residents

The fourth and final solution space describes what we call smart grid residents. As with smart residents, control over energy use remains manual, driven by residents in the home, but agency switches to focus on the grid and third party actors. This is related to the concept of "energy citizenship" discussed in the literature on energy consumption (ex. Devine-Wright 2007; Goulden et al. 2014) in which individuals accept equal responsibility for managing energy use for collective benefit. In this scenario, third parties seek to influence the behavior of residents through the provision of information, resulting in several control scenarios. In the first, third parties provide persuasive information or incentives to residents that lead them to remotely control devices through smart technologies in a way that benefits the grid. Alternatively, third parties deploy persuasive smart technologies that provide information to either change the ways in which residents interact with end uses or the ways in which they remotely control those end uses through smart technologies themselves. Here, primary agency resides with the third parties, seeking to cultivate services to support the grid.

Example thermostat use case: Within this type of smart home, residents partake in voluntary behavioral changes that reduce energy use or provide demand flexible resources by adjusting the use of their thermostat based on requests from third parties or based on suggestions made by the smart technologies. For example, a third party aggregator selling demand flexibility to the regional electricity markets may request the resident change preferred setpoints in their thermostat or allow the thermostat to reduce the setpoints at a specific time to address periods of peak demand (ex. on a hot summer afternoon) or supply shortage (ex. during a solar eclipse). An example of this scenario is provided by the business model of OhmConnect (OhmConnect 2020) who reward customers for making behavioral changes that reduce home energy use during a peak demand hour of the day. Assumptions here presume that the resident will prioritize the needs of the grid over other competing goals in the home, engage with smart technologies, and take actions accordingly.

Discussion

Research in the realm of smart technologies and DSM has already begun to question the accuracy of many of the assumptions underlying each of the smart home configurations we identify. Initial programs and pilots have shown that residents may be willing to give up control to third parties or smart technologies in certain situations but not others (Hansen and Hauge 2017; Fell et al 2015), and that programs relying on purely automated capabilities of devices may

vastly under perform when it comes to delivering on expected energy benefits (ex. Pritoni Woolly and Modera 2016). Further evidence has shown that residents are not as absent from systems using automated controls as expected, using technologies in innovative and unexpected ways (Nyborg 2015; Nicholls Strengers and Tirdao 2017) or more actively managing energy use than predicted (Sintov White and Walpole 2019), outcomes that may not necessarily result in energy benefits. In addition, existing evidence on the impacts of these technologies stems primarily from early adopter populations, leaving questions regarding their impacts on more vulnerable populations (ex. low income, renters) who may not be able to afford these new technologies and the related infrastructures, or who may face adverse costs when they are used to address grid needs (Nicholls Strengers and Tirado 2017).

As noted by Elliot and colleagues (2012, 47) when discussing the application of smart technologies to drive energy savings, "Intelligent efficiency rests on carefully considered combinations of relying on technologies (not humans) where that maximizes efficiency and inviting human interaction where that is optimal". The authors further suggest that intelligence invites or disinvites resident engagement depending on the forecasted energy impacts. This underscores the need to find the "right" degree of control for the right situations, acknowledging that many humans already hold an a certain level of intelligence related to how they operate their homes and this human intelligence can be hard to replicate or replace with artificial intelligence (Karjalainen 2013). Scenarios developed through this taxonomy could be coupled with customer segmentation efforts to identify predictors of which types of households might be more willing to participate in different solutions (ex. similar to work recently published by Mazur-Stommen et al. 2020). Alternatively, it could inform the development of simulation tools aiming to evaluate tradeoffs between different solution spaces as a way to further assess potential impacts and underlying assumptions.

While a promising start, this taxonomy remains in the initial phases of development thus making it ripe for further development into a robust decision support tool. Future research could continue to refine this taxonomy to better represent certain system dynamics, such as those around flows of information (which were largely kept constant across our scenarios) or more complex representation of the various third party actors (ex. utilities, smart technology providers, or demand aggregators). Future iterations could more explicitly discuss issues surrounding which energy benefits are more likely to be derived in a given situation (McIlvennie, Sanguinetti, and Pritoni, 2020) and which actors are the primary recipients of those benefits. In addition, the framework could be used as a way to analyze risks (ex. lack of behavioral persistence or human override of automation) to implementing certain smart home solutions in specific contexts given population characteristics.

Moving forward, the question is not only what the right type of control or level of automation is but the right type of control for which households or grid contexts. Previous research (Goulden et al 2014; Wilhite and Diamond 2017) has noted that while a highly automated version of the smart home (i.e. the smart home or smart grid home in our taxonomy) might successfully drive energy benefits in some scenarios, focusing on these scenarios alone will limit overall potential of the system to meet sustainability related objectives. Wilhite and Diamond (2017, 56) observe that overly technical solutions may "lock in" certain behaviors and that "The tendency to lock house and technology design into 'one size fits all' perpetuates a tendency in energy policy to neglect the diversity of household needs, knowledge, and capacity to engage with complex systems." We believe this taxonomy could be a powerful tool to help fend off such lock in, acknowledge the diversity of solutions that exist to manage home energy

use, and help deploy an array of programs in a way that meets both sustainability and grid-related objectives in addition to those of residents in the home.

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